



Signals of single particle production at the earliest LHC

Riccardo Barbieri^{a,b}, Riccardo Torre^{b,c,*}

^a Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy

^b INFN, Sezione di Pisa, Largo Fibonacci 3, I-56127 Pisa, Italy

^c Università di Pisa, Dipartimento di Fisica, Largo Fibonacci 3, I-56127 Pisa, Italy

ARTICLE INFO

Article history:

Received 6 September 2010

Accepted 16 November 2010

Available online 20 November 2010

Editor: G.F. Giudice

Keywords:

Early LHC phenomenology
Phenomenological Lagrangians
Resonant production
Scalar resonance
Heavy fermion

ABSTRACT

Based on simple phenomenological Lagrangians, fulfilling reasonable consistency conditions, we consider under which circumstances the production of a single particle might be an early signal of new physics at the LHC. Effective final states are $\gamma\gamma$ and $\gamma + \text{jet}$ already with tens of inverse picobarns of integrated luminosity at 7 TeV.

© 2010 Elsevier B.V. Open access under CC BY license.

1. Introduction

The beginning of LHC operation at half the foreseen center-of-mass energy and with an unavoidably low initial luminosity brings the focus on possible signals of new physics that might show up at all in the early stages of operation. Model-building prejudices normally play an important role in determining the search strategies. While this is understandable, here we set aside such prejudices as much as possible. We base our considerations on simple phenomenological Lagrangians, fulfilling reasonable consistency conditions. We are generally guided by the possible existence of composite states produced by a putative strong dynamics responsible for ElectroWeak Symmetry Breaking (EWSB), but we aim mostly at a neat and simple definition of the interactions responsible for the signals under discussion. We think that this should also represent an appropriate guide in the presentation of the experimental results, to maximize their usefulness for any subsequent consideration.

Single production of a relatively narrow resonance is the most obvious candidate for a copious source of new physics signals in the early stages of LHC operation. Very much studied is the case of a vector resonance produced in the $q\bar{q}$ -channel, either neutral or charged, with its leptonic decay modes [1,2]. In fact, the multiplicity of partonic channels in a pp collider makes several different cases possible. As a matter of fact, in the competition with the Tevatron with its integrated luminosity already available, the $q\bar{q}$ -channel is definitely less favourable relative to the quark–quark, quark–gluon and gluon–gluon channels in view of the corresponding parton luminosities. We therefore concentrate our attention to these channels. If one considers in each of them the lowest possible spin and the lowest possible QCD representation, for matter of simplicity, the cases of interest are:

- **gg -channel:** a spinless totally neutral scalar S ;
- **qg -channel:** a $J = 1/2$ colour-triplet “heavy quark”, either “ U ” or “ D ”;
- **qq -channel:** a spinless colour-triplet or colour-sextet ϕ , with various possible charges.

We assume that one single new particle is available at a time, which therefore can only decay into Standard Model (SM) particles. We concentrate our attention to the first two cases, since the scalar triplet, or sextet [3], can only decay into a pair of jets, consistently with known constraints, whereas we find relatively more promising the final states containing at least one photon. The resonance in the qq channel suffers also of problems with flavour physics (see below).

* Corresponding author at: Università di Pisa, Dipartimento di Fisica, Largo Fibonacci 3, I-56127 Pisa, Italy.
E-mail address: riccardo.torre@pi.infn.it (R. Torre).

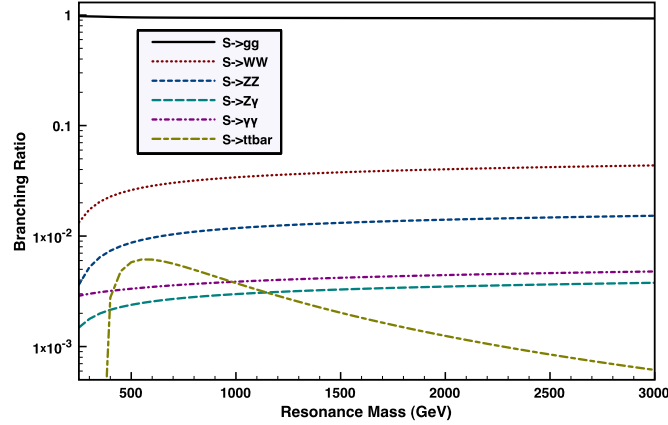


Fig. 1. Branching ratios as functions of the scalar mass M_S for $c_i = 1$.

2. Neutral scalar singlet S

The reference Lagrangian that we adopt is the following,

$$\mathcal{L}_S = c_3 \frac{g_S^2}{\Lambda} G_{\mu\nu}^a G^{\mu\nu a} S + c_2 \frac{g^2}{\Lambda} W_{\mu\nu}^i W^{\mu\nu i} S + c_1 \frac{g'^2}{\Lambda} B_{\mu\nu} B^{\mu\nu} S + \sum_f c_f \frac{m_f}{\Lambda} \bar{f} f S, \quad (2.1)$$

where Λ is an energy scale, the c_i , $i = 1, 2, 3, f$, are dimensionless coefficients and f is any SM fermion, of mass m_f . S is a scalar of mass M_S , totally neutral under the SM gauge group. A coupling of S to the Higgs doublet of the form $m_S S H^+ H$ could also be present, as it would actually be induced by radiative corrections. In a wide range of M_S and Λ it is however consistent to assume that such coupling is irrelevant.

The two body widths of S are given by

$$\Gamma(S \rightarrow gg) = \frac{2c_3^2 g_S^4 M_S^3}{\pi \Lambda^2}, \quad (2.2a)$$

$$\Gamma(S \rightarrow W^+ W^-) = \frac{c_2^2 g^4 \sqrt{M_S^2 - 4M_W^2} (M_S^4 - 4M_S^2 M_W^2 + 6M_W^4)}{2\pi M_S^2 \Lambda^2}, \quad (2.2b)$$

$$\Gamma(S \rightarrow ZZ) = \frac{(c_2 g^2 \cos^2 \theta_W + c_1 g'^2 \sin^2 \theta_W)^2 \sqrt{M_S^2 - 4M_Z^2} (M_S^4 - 4M_S^2 M_Z^2 + 6M_Z^4)}{4\pi M_S^2 \Lambda^2}, \quad (2.2c)$$

$$\Gamma(S \rightarrow Z\gamma) = \frac{\sin^2 \theta_W \cos^2 \theta_W (c_1 g'^2 - c_2 g^2)^2 (M_S^2 - M_Z^2)^2}{2\pi M_S^3 \Lambda^2}, \quad (2.2d)$$

$$\Gamma(S \rightarrow \gamma\gamma) = \frac{(c_1 + c_2)^2 e^4 M_S^3}{4\pi \Lambda^2}, \quad (2.2e)$$

$$\Gamma(S \rightarrow t\bar{t}) = \frac{3c_t^2 m_t^2 (M_S^2 - 4m_t^2) \sqrt{M_S^2 - 4m_t^2}}{8\pi M_S^2 \Lambda^2}, \quad (2.2f)$$

with the corresponding branching ratios shown in Fig. 1 as functions of M_S for all $c_i = 1$, which we take as reference case. The total width of S scales as $1/\Lambda^2$. Λ is an arbitrary mass parameter, which we take for illustrative purposes at 3 TeV, reminiscent of a new strong interaction at $\Lambda \approx 4\pi v$, possibly responsible for EWSB. If S was a composite particle in (2.1) by the strong dynamics, Naive Dimensional Analysis (NDA) [4,5] would suggest $c_i \approx 1/4\pi$. Larger values could however arise from large N and/or from more drastic assumptions about the nature of the gauge bosons. For $\Lambda = 3$ TeV and $c_i = 1$, Γ_S goes from about 10 GeV at $M_S = 500$ GeV to about 250 GeV for $M_S = 1.5$ TeV.

We have made a preliminary study of the sensitivity to the search for S in the di-jet, $\gamma\gamma$ and γZ channels. The results for the first two cases are illustrated in Fig. 2 for $M_S = 0.5$ and $M_S = 1$ TeV respectively. While it appears difficult to see an emerging signal in the di-jet final state, taking into account of systematic uncertainties, a discovery looks possible in the $\gamma\gamma$ channel with a modest luminosity of about 10–100 pb $^{-1}$, as illustrated in Fig. 3. In the case of γZ channel one would have to pay for an extra factor of about 20–40 in the needed luminosity.

All this is trivially extendible to arbitrary values of Λ and c_i . For a given integrated luminosity the absence of signal in $\gamma\gamma$, assuming the dominance of $S \rightarrow gg$, is easily translated in a lower bound on $\Lambda/(c_1 + c_2)$.

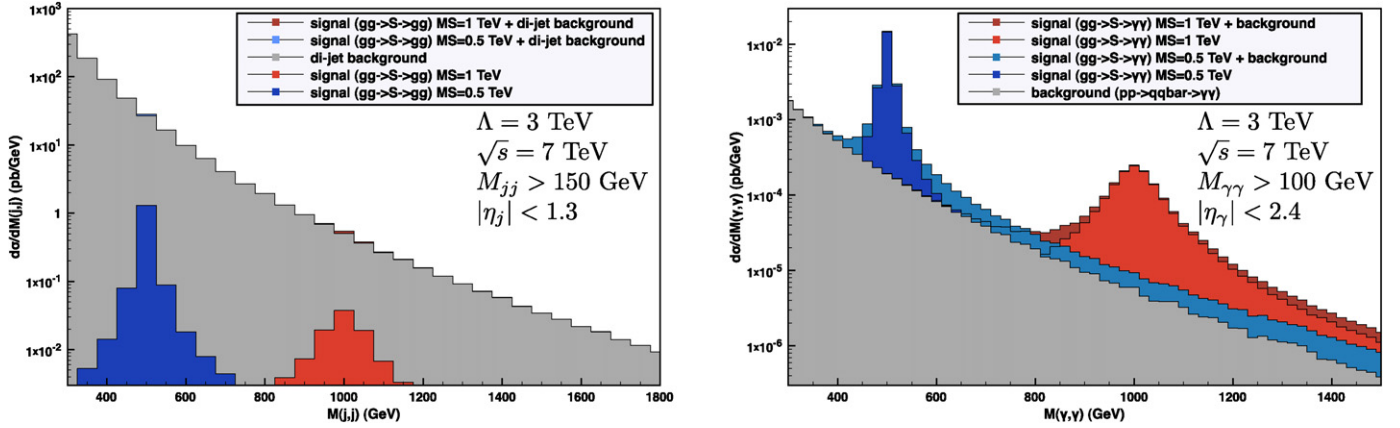


Fig. 2. Signals of a 500 GeV (blue) and 1 TeV (red) scalar singlet S in the di-jet (left panel) and $\gamma\gamma$ (right panel) invariant mass distributions vs the SM background at the early LHC ($\sqrt{s} = 7$ TeV). $\Lambda = 3$ TeV, $c_i = 1$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

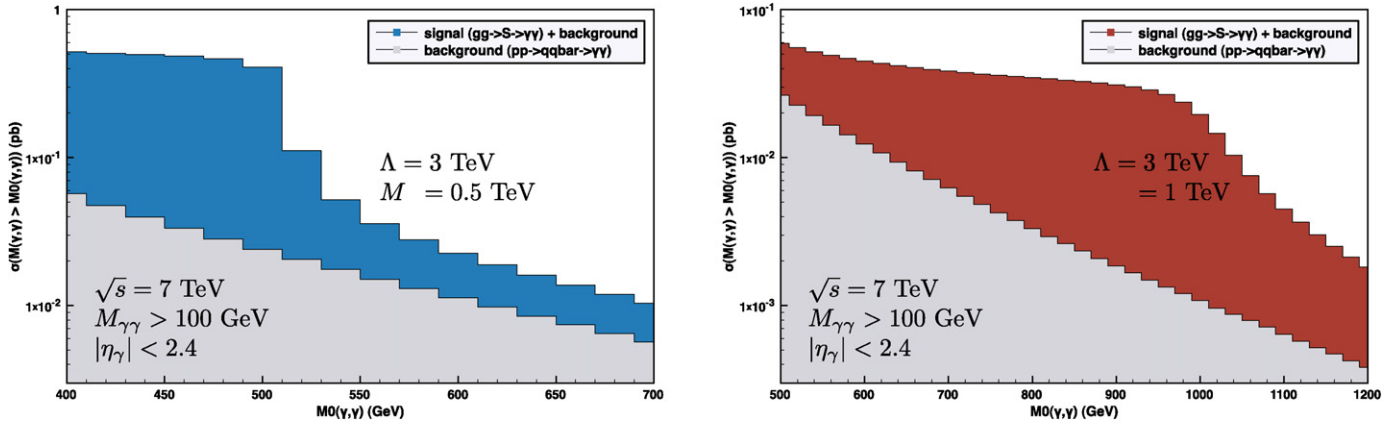


Fig. 3. Number of events for $\int \mathcal{L} dt = 1 \text{ pb}^{-1}$ at LHC (7 TeV) with $\gamma\gamma$ invariant mass greater than $M_0(\gamma, \gamma)$ for a 500 GeV (left panel) and a 1 TeV (right panel) scalar singlet S . $\Lambda = 3$ TeV, $c_i = 1$.

3. Heavy quark U

In analogy with (2.1), to describe the interactions of a heavy U -type quark of mass M_U with the SM particles we consider the interaction Lagrangian

$$\mathcal{L}_U = c_G \frac{g_S}{\Lambda} \bar{U}_L \sigma^{\mu\nu} T^a u_R G_{\mu\nu}^a + c_B \frac{g'}{\Lambda} \bar{U}_L \sigma^{\mu\nu} u_R B_{\mu\nu} + \text{h.c.}, \quad (3.1)$$

where $\sigma^{\mu\nu} = i/2[\gamma^\mu, \gamma^\nu]$ and T^a are the generators of the fundamental representation of $SU(3)$ ($T^a = \lambda^a/2$). U transforms therefore as a $(3, 1)_{2/3}$ of the SM gauge group. As in the case of the scalar S , U could be a composite state by a strong dynamics responsible for EWSB, in which case NDA suggests $\Lambda \approx 4\pi v \approx 3$ TeV and $c_G \approx c_B \approx 1/4\pi$.

Note that the Lagrangian (3.1) does not break the chirality of the standard u -quark, which is crucial to preserve its lightness. A problem with flavour arises, however, since we pretend that U couples to the physical standard u -quark but has no (significant) coupling to the c -quark, not to cause unobserved $\Delta C = 2$ flavour changing effects. In other words the coupling in (3.1) would have to be particularly aligned with the standard Yukawa matrix for the up-type quarks. While this is not excluded, a neater way to get around this problem would be to introduce three U -fields, one per generation, and assume that the Lagrangian (3.1) respects a global $SU(3)_R$ acting on the standard three up-type quarks. In either case the following considerations apply.¹

To study the sensitivity to U , as in the case of the singlet S we consider the reference values $\Lambda = 3$ TeV and $c_G = c_B = 1$. The two body widths of U are given by

$$\Gamma(U \rightarrow ug) = \frac{4\alpha_S M_U^3}{3\Lambda^2}, \quad (3.2a)$$

$$\Gamma(U \rightarrow uZ) = \frac{g'^2 \sin^2 \theta_W \sqrt{M_U^2 - 4M_Z^2} (2M_U^4 - M_Z^2 M_U^2 - M_Z^4)}{8\pi M_U^2 \Lambda^2} \approx \frac{\alpha M_U^3 \tan^2 \theta_W}{\Lambda^2}, \quad (3.2b)$$

¹ Analogous considerations hold for the scalar states in the qq -channel. For example in the case of the uu -channel one would have to introduce a $SU(3)_R$ -sextet of highly degenerated ϕ 's.

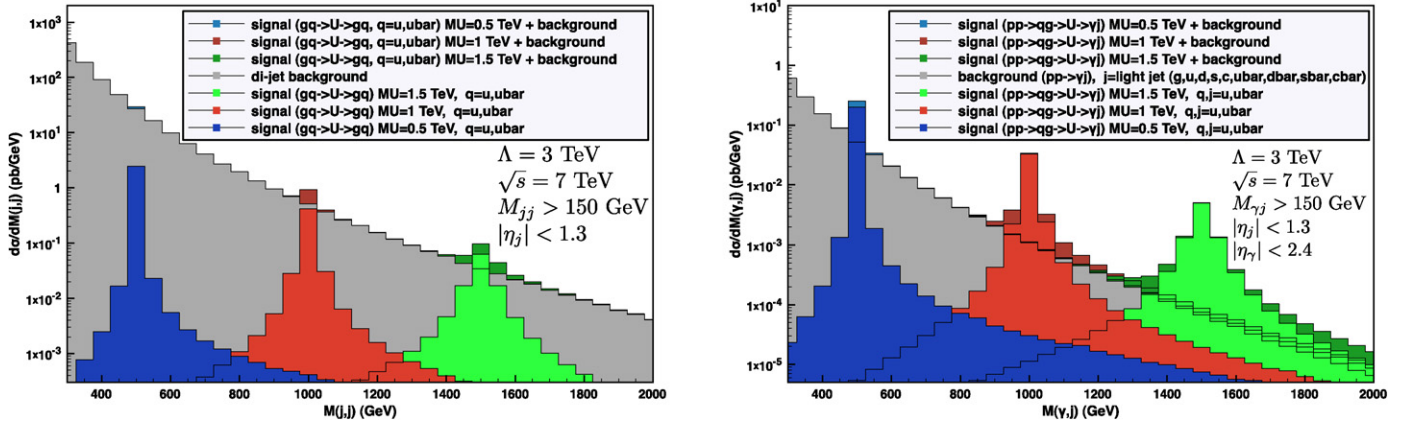


Fig. 4. Signals of a 500 GeV (blue), 1 TeV (red) and 1.5 TeV (green) heavy quark in the di-jet (left panel) and $\gamma + jet$ (right panel) invariant mass distribution vs. the SM background at the early LHC ($\sqrt{s} = 7$ TeV). $\Lambda = 3$ TeV, $c_t = 1$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

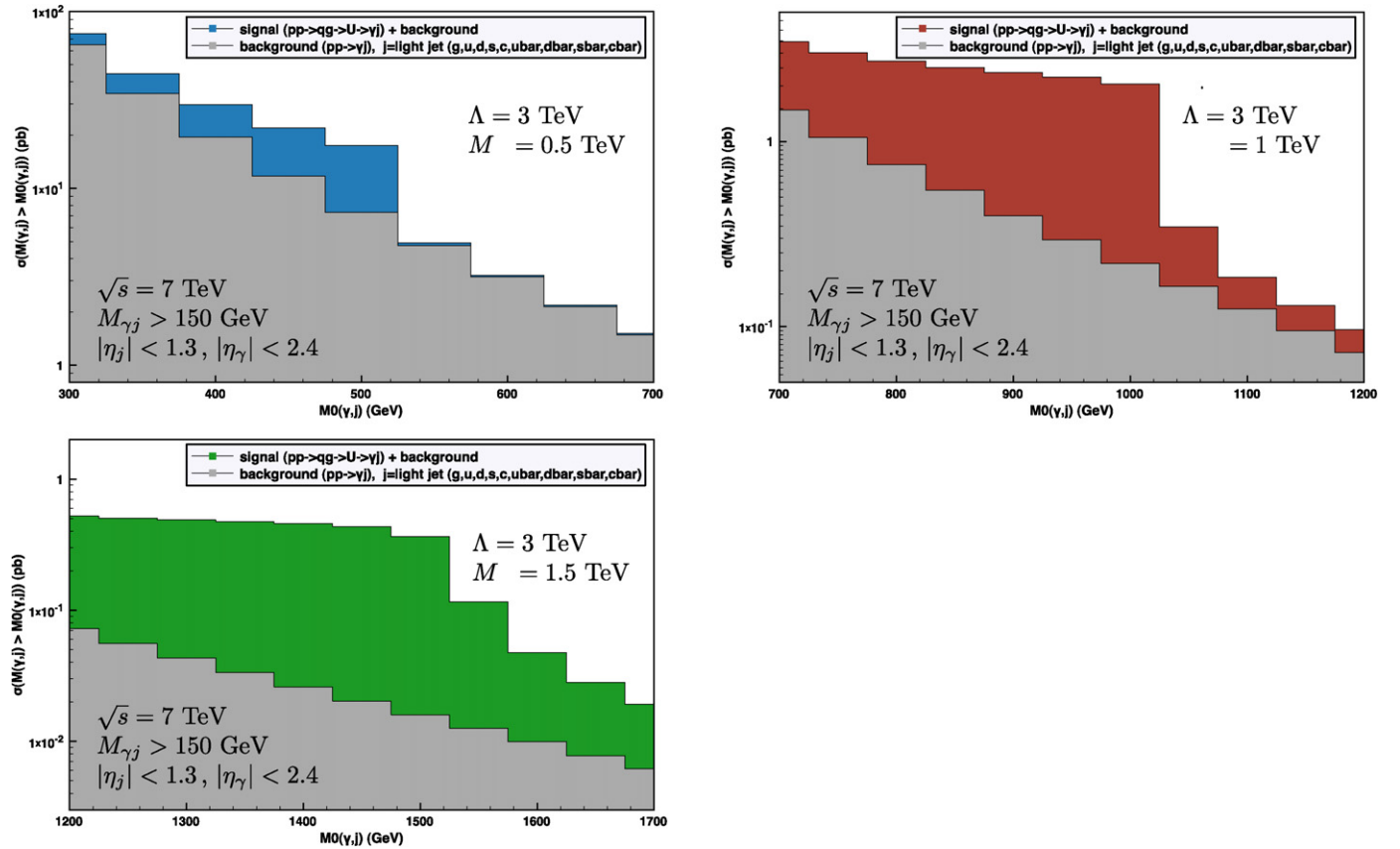


Fig. 5. Number of events for $\int \mathcal{L} dt = 1 \text{ pb}^{-1}$ at LHC (7 TeV) with $\gamma + jet$ invariant mass greater than $M_0(\gamma, j)$ for a 500 GeV (top left panel), a 1 TeV (top right panel) and a 1.5 TeV (bottom left panel) heavy quark. $\Lambda = 3$ TeV, $c_t = 1$.

$$\Gamma(U \rightarrow u\gamma) = \frac{\alpha M_U^3}{\Lambda^2}, \quad (3.2c)$$

so that the total width,

$$\Gamma_U \approx \frac{M_U^3 \alpha_S}{\Lambda^2} \left(\frac{4}{3} + \frac{\alpha}{\alpha_S \cos^2 \theta_W} \right), \quad (3.3)$$

ranges from about 2 GeV to about 30 GeV for $M_U = 0.5$ to $M_U = 1.5$ TeV. Almost irrespective of the U mass, the dominant ug decay mode has a branching ratio of about 92%, whereas the $u\gamma$ and uZ modes have BRs of about 6% and 2% respectively.

As in the case of S , we have made a preliminary study of the sensitivity to the search for the heavy U in the di-jet, $\gamma + jet$ and $Z + jet$ channels. The results for the first two cases are illustrated in Fig. 4 for $M_U = 0.5, 1$ and 1.5 TeV respectively. While it appears difficult to see an emerging signal in the di-jet final state, taking into account of systematic uncertainties, a discovery looks possible in the $\gamma + jet$

channel with a modest luminosity of about 5 or 10 pb^{-1} , as illustrated in Fig. 5. The $Z + \text{jet}$ channel would require luminosities in the hundreds of inverse picobarns.

4. Conclusions

The lack so far of a thorough experimental exploration of the energy range at or well above the Fermi scale, the most fundamental scale in particle physics as presently known, calls for an open attitude in the expectation for possible signals of new physics. In turn this has a twofold general implication. On one side one must be ready for surprises. On the other side it is essential that the experimental results be analysed and presented in the neatest possible way with a minimum of biases.

In this work we have attempted to apply this attitude to the discussion of possible signals of new physics in the early stages of LHC operation, concentrating our attention to the production of a relatively narrow resonance that can compete with the well studied case of a neutral vector. While we have generally in mind a possible composite state produced by a putative strong dynamics responsible for EWSB, the important thing is that the interaction that produces one of these states be clearly and simply defined. This is the case for the phenomenological Lagrangians (2.1) and (3.1) with a single interaction term responsible for the production for the singlet scalar S or for the triplet fermion U respectively.

With a suitable guess for the decay branching ratios we have found that final states in a pair of photons for S or in a photon plus jet for U may lead to detectable signals already with a few tens of picobarns of integrated luminosity at 7 TeV. For this to be the case we may have used an optimistic value for the strength of the relevant couplings. While such values cannot in any case be excluded a priori and, to the best of our knowledge, have not been excluded at the Tevatron so far, the progression of the integrated luminosity achievable at the LHC can quickly explore fully relevant regions for these couplings. Meanwhile, with a defined and simple single coupling for the production of S or U , the experimental results for a narrow resonance in the $\gamma\gamma$ or in the $\gamma + \text{jet}$ channels can be usefully given as a plot of $d\sigma/dM \cdot BR$ versus the invariant mass of the final state channel. We think that the interpretation of a possible positive signal in terms of more elaborate and more defined theoretical models would be eased by this way of presenting the data.

Acknowledgements

We thank Michelangelo Mangano, Riccardo Rattazzi and Slava Rychkov for useful comments. This work is supported in part by the European Programme “Unification in the LHC Era”, contract PITN-GA-2009-237920 (UNILHC) and by the MIUR under the PRIN contract 2008XM9HLM.

References

- [1] See the review “ Z' -boson searches” in C. Amsler, et al., Particle Data Group, Phys. Lett. B 667 (2008) 1.
- [2] For a recent relevant work see E. Salvioni, A. Strumia, G. Villadoro, F. Zwirner, JHEP 1003 (2010) 010, arXiv:0911.1450 [hep-ph].
- [3] C.W. Bauer, Z. Ligeti, M. Schmaltz, J. Thaler, D.G.E. Walker, Phys. Lett. B 690 (2010) 280, arXiv:0909.5213 [hep-ph].
- [4] A. Manohar, H. Georgi, Nucl. Phys. B 234 (1984) 189.
- [5] A.G. Cohen, D.B. Kaplan, A.E. Nelson, Phys. Lett. B 412 (1997) 301, arXiv:hep-ph/9706275.